12. Radiological Dose Assessment

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Introduction

Radiological doses to the public result from both natural and man-made radiation. The total dose to different populations can be determined by measurements and calculations. This chapter describes LLNL's radiological dose assessments, made to determine the impact of LLNL operations, and contains a discussion of the analyses we performed to demonstrate LLNL's compliance with the National Emission Standards for Hazardous Air Pollutants (NESHAPs).

Because this report is distributed outside the scientific community, we have included a brief preliminary discussion to enable the nontechnical reader to understand more easily the radiological dose assessment information we report. For more information, see *Radiation: Doses, Effects, Risks* (U.N. Environment Programme 1985).

Natural and Man-Made Radiation

By far the greatest part of radiation received by the world's population comes from natural sources—primarily cosmic rays that impinge on the earth's atmosphere from space and radionuclides naturally present in our environment, such as radioactive materials in soil and rocks. Among these terrestrial sources are carbon-14, potassium-40, rubidium-87, uranium-238, thorium-232, and the radioactive elements, such as radon, that arise following decay of uranium and thorium. The source of human exposure to natural radiation can be external (from substances staying outside the body) or internal (from substances inhaled in air or ingested in food and water). Individual doses vary with location. The level of cosmic radiation increases with altitude, because there is less air overhead to act as a shield, and the earth's poles receive more cosmic radiation than the equatorial regions, because the earth's magnetic field diverts the radiation. The levels of terrestrial radiation differ from place to place around the United States and around the world, mainly due to variations in soil and rock composition.

Adding to this pervasive natural or background radiation is man-made radiation from radionuclides used in medicine, consumer products, the production of energy, and the production of nuclear weapons. Exposure to man-made sources can be controlled more readily than exposure to most natural sources. However, nuclear explosives tested in the atmosphere in the 1950s–1960s spread radioactivity across the surface of the globe, and the nuclear reactor accident at Chernobyl affected a large area. At present, medical treatment is the largest common source of public exposure to man-made radiation. Individual medical doses vary enormously—someone who has never had an x-ray examination may

receive zero medical dose while patients undergoing treatment for cancer may receive many thousands of times the annual average dose from natural radiation. Another source of public exposure to man-made radiation is consumer products, including luminous-dial watches, smoke detectors, airport x-ray baggage inspection systems, and tobacco products.

Radioactivity

Generally, naturally occurring isotopes are stable, but notable exceptions include carbon-14, potassium-40, thorium-232, uranium-235, and uranium-238, which are naturally occurring but radioactive. Nuclear decay divides into three main categories: alpha, beta, and gamma. Alpha decay is the spontaneous emission of an alpha particle (a bound state of two protons and two neutrons—the nucleus of a helium atom) from a nucleus containing a large number of protons (most commonly 82 or more). Beta decay is the spontaneous conversion of a neutron to a proton in the nucleus with the emission of an electron, and gamma decay is the spontaneous emission of high-energy photons (high-frequency electromagnetic radiation) by nuclei.

Radioisotopes decay at quite different rates; the "half-life," or length of time for half of the atoms to decay, spans a wide range from small fractions of a second to millions of years. For example, tritium (the radioactive form of hydrogen) has a 12.3-year half-life, compared to 24,131 years for plutonium-239.

Some radioisotopes undergo a decay chain, forming radioisotopes that decay into other radioisotopes until a stable state is achieved. For example, an atom of uranium-238 can undergo alpha decay, leaving behind a daughter, thorium-234, which is also radioactive. The transformations of the decay chain continue, ending with the formation of lead-206, which is a stable isotope.

Radioactivity can be hazardous because radiation (alpha particles, beta particles, or gamma rays) can be released with great energy. It is capable of altering the electronic configuration of atoms and molecules, especially by stripping one or more electrons off the atoms of the irradiated material, thereby disrupting the chemical activity in living cells. If the disruption is severe enough to overwhelm the normal restorative powers of the cell, the cell may die or become permanently damaged. Cells are exposed to many naturally occurring sources of chemical disruption, including naturally toxic chemicals in food, microbes that cause disease, high-energy radiation from outer space (cosmic rays), and heat and light (including the sun's rays, which can cause sunburn and skin cancer). Consequently, cells and living organisms have evolved the capacity to survive limited amounts of damage, including that caused by naturally occurring radioactivity.

Three main factors determine the radiation-induced damage that might be caused to living tissue: the number of radioactive nuclei that are present, the rate they give off energy, and the effectiveness of energy transfer to the host medium, i.e., how the radiation interacts with the tissue. Alpha radiation can be halted by a piece of paper and can scarcely penetrate the dead outer layers of skin. Radioisotopes that give off alpha radiation are generally not health hazards unless they get inside the body through an open wound or are ingested or inhaled. In those cases, alpha radiation can be especially damaging because its disruptive energy can be deposited within a small distance, resulting in significant energy deposited in a few cells. Beta radiation from nuclear decay typically penetrates a centimeter or two of living tissue. It therefore deposits energy over many cells, decreasing the damage to any single cell. Gamma radiation is extremely penetrating and can pass through most materials, only being significantly attenuated by thick slabs of dense materials, such as lead.

Measurement of Radioactivity and Dose

The rate that a nucleus decays is expressed in units of becquerels, abbreviated Bq, where one becquerel is one decay per second, or alternatively in curies, Ci, where one curie equals 3.7×10^{10} (37 billion) decays per second, or 3.7×10^{10} Bq (approximately equal to the decay rate of 1 gram of pure radium). Becquerels and curies are not measures of the effect of radiation on living tissue. This depends on the efficiency of energy deposition as the radiation traverses matter.

The amount of energy deposited in living tissue is called the "dose." The amount of radiation energy absorbed per gram of tissue is called the "absorbed dose," and is expressed in units of rads or grays (Gy), where 1 Gy equals 100 rads. Because an absorbed dose produced by alpha radiation is more damaging to living tissue than the same dose produced by beta or gamma radiation, the absorbed dose is multiplied by a quality factor to give the dose equivalent. The quality factor for alpha radiation is 20; for beta and gamma, 1. The dose equivalent is measured in units of rem or sievert (Sv); 1 Sv equals 100 rem. Also commonly used are millirem (mrem) and millisievert (mSv), which are one-thousandth of a rem and sievert, respectively.

Just as one type of radiation can be more damaging than others, some parts of the body are potentially more vulnerable to radiation damage than others, so the different parts of the body are given weightings. For example, a given radiation dose from iodine-131 is more likely to cause cancer in the thyroid than in the lung. The reproductive organs are of particular concern because of the potential risk of genetic damage. Once particular organs are weighted appropriately, the dose equivalent becomes the "effective dose equivalent," also expressed in rem or sievert.

The effective dose equivalent describes doses to individuals. When individual effective dose equivalents received by a group of people are summed, the result is called the "collective effective dose equivalent" and is expressed in person-sievert or person-rem. Finally, to account for the long-term effects of radionuclides as they continue to decay and affect generations of people, we calculate the dose over many years, summing the effect over time. This is termed the "collective effective dose equivalent commitment." Most of our discussion in this chapter deals with the effective dose equivalent and the collective effective dose equivalent.

Doses from Natural and Man-Made Radioactivity

The average radiation dose from natural sources in the United States, according to the National Council on Radiation Protection and Measurement (NCRP; 1987b), is 3.0 mSv / y (300 mrem / y). Approximately 0.3 mSv / y (30 mrem / y) of this exposure comes from high energy radiation from outer space (cosmic rays). Terrestrial sources, mainly radionuclides in rock and soil, also account for approximately 0.3 mSv / y (30 mrem / y) of the average natural dose. Another significant part of the dose comes from radionuclides we ingest through food and drink, resulting in approximately 0.4 m Sv / y (40 mrem / y). Potassium-40 and carbon-14 are common radionuclides in food.

The remaining 2.0 mSv / y (200 mrem / y) or 67% of the average dose from natural sources in the United States comes from radon gas. Radon is one of the major radionuclides produced by uranium decay, and our inhalation dose is dominated by radon's short-lived decay products. **Figure 12-1** shows the distribution of annual radiation doses from natural and other common sources.

Radon dose varies significantly with geographic location. Levels several times higher than the average occur in some regions of the U.S., while at LLNL and its environs doses as low as half the average are typical. Radon gas seeps out of the earth worldwide. Radon in water and natural gas provide additional but less important sources of radon in homes. Consumption of water high in radon is not the main exposure source; a greater exposure is believed to arise from inhalation of radon in water vapor when showering. The United States Environmental Protection Agency (EPA) has instituted a major program to educate the public regarding the effects of naturally occurring radon (U.S. Environmental Protection Agency and U.S. Department of Health and Human Services 1986).

Medical treatment is the largest common source of public exposure to man-made radiation, and most of it is from medical x-rays. These contribute 0.39 mSv (39 mrem) to the average whole-body dose in the United States, but individual doses vary enormously. For example, a typical dental x-ray series results in a skin dose (not whole body) of approximately 2.5 mSv (250 mrem). Nuclear

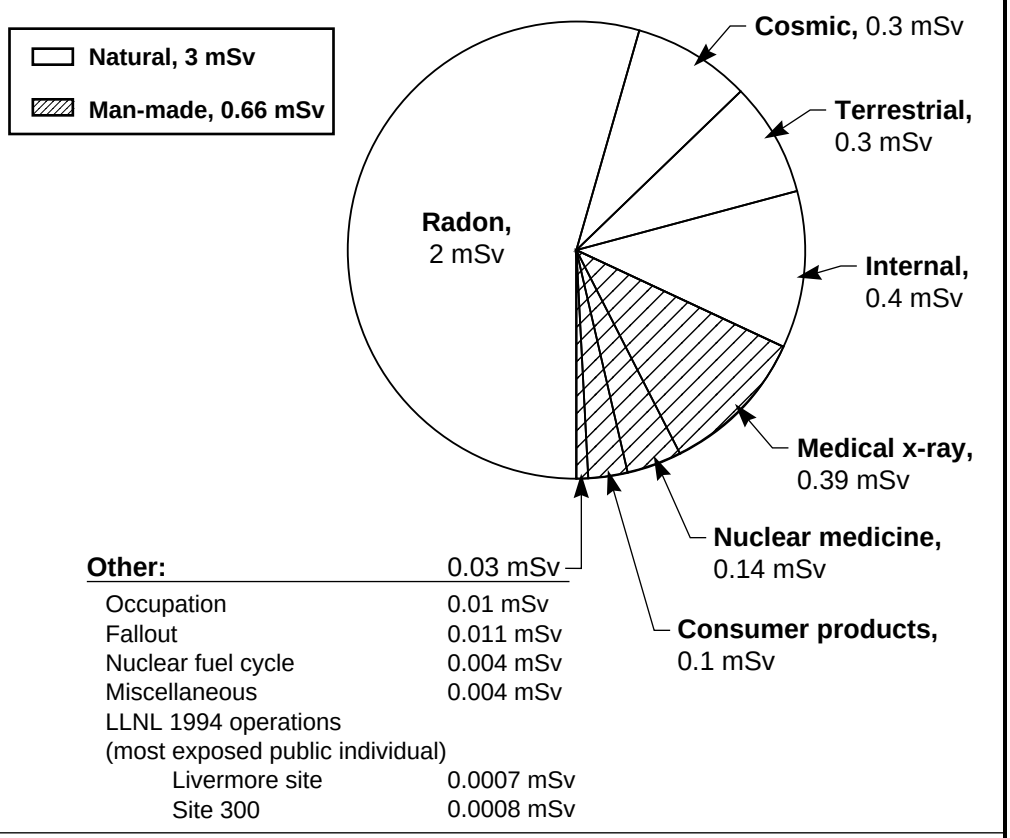

Figure 12-1. Typical annual radiation doses from natural and man-made sources (National Council on Radiation Protection and Measurements 1987b).

medicine contributes 0.14 mSv (14 mrem) to the average dose, and consumer products add 0.1 mSv (10 mrem). For a typical member of the public, radiation from medical procedures and consumer products result in a dose of approximately 0.63 mSv / y (63 mrem / y). The average dose from other man-made sources, including fallout from nuclear testing, is less than 0.03 mSv (3 mrem). As will be described in the following sections, the contributions from LLNL operations to the dose of even the most affected resident would not be discernible on the scale shown in **Figure 12-1**; these contributions are listed under "Other" in the figure, anticipating our conclusions presented near the end of this chapter.

Radiation Sources, Control Measures, and Standards

Radioisotopes used at LLNL include uranium, transuranics, biomedical tracers, tritium, and mixed-fission products. This section describes control measures taken to minimize both worker and off-site exposures, and presents the federal standards defining allowable radiation exposures to the public from operations at DOE facilities.

LLNL's Radiation Control Program

Protection of employees and the public from the uncontrolled release of radioactive materials into the environment is a primary consideration for LLNL. This effort consists of several stages. First, when an operation or facility is designed, a thorough assessment of potential radiation hazards is conducted, and radioisotope-handling procedures and work enclosures are determined for each project, depending on the isotope, the quantity being used, and the type of operations being performed. Radioisotope handling and working environments include glove boxes, exhaust hoods, and laboratory bench tops. The controls might include limiting physical access and using shielding, filters, and remote handling equipment. Facility Safety Analysis Reports and Facility Safety Procedures are written to document the need for these measures and to specify the requirements for maintenance, training, emergency response, and other administrative control measures.

Another stage of the radiation control program comes into play when a facility is occupied for use. Prior to the conduct of an operation in the facility, an Operational Safety Procedure (OSP) is written that specifies the actions to be taken in conducting a research or development project. This procedure is reviewed by environmental analysts, industrial hygienists, and health physicists. These reviews assess the safety of the operation, its compliance with current occupational health and environmental standards, and the adequacy of proposed engineering and administrative controls. The OSP also specifies training requirements for personnel performing the procedure. This part of the control program enables LLNL personnel who work with radiation and radioactivity to recognize and prevent the execution of unsafe operations.

The last stage of the radiation control program involves direct monitoring of the workplace environment. This includes sampling of the air and surfaces in facilities where radioactive materials are handled, and includes the surveillance and effluent monitoring of radiation in air and water, as discussed in Chapters 2 and 4 through 11 of this report. Finally, it includes personal dosimetry and bioassay programs used to monitor potential worker exposure to direct radiation and radioactive isotopes. This monitoring program measures the effectiveness of a facility's radiation control program as well as providing information on worker exposures.

Radiation Protection Standards

DOE environmental radiation protection standards are provided in DOE Order 5400.5, *Radiation Protection of the Public and the Environment,* which incorporates standards for controlling exposures to the public from operations at DOE facilities. These standards are based on recommendations by the International Commission on Radiological Protection (ICRP 1977, 1980) and the National Council on Radiation Protection and Measurements (NCRP 1987a). The

primary DOE radiation standards for protection of the public are 1 mSv/y (100 mrem/y) effective dose equivalent for prolonged exposure, and 5 mSv/y (500 mrem/y) effective dose equivalent for occasional exposure. These limits are based on the dose to the maximally exposed individual in an uncontrolled area, and include all pathways of exposure. The limits apply to the sum of the effective dose equivalent from external radiation and the committed (50-y) effective dose equivalent from radioactive materials that may remain in the body for many years after being ingested or inhaled.

DOE and LLNL also comply with the EPA's standard for radiation protection, promulgated under Section 112 of the Clean Air Act, as amended. This EPA radiation dose standard, which applies to air emissions, is defined in Subpart H of NESHAPs under 40 CFR 61. It limits to 0.1 mSv/y (10 mrem/y) the whole-body effective dose equivalent to members of the public from DOE activities. Before December 15, 1989, the standard was 0.25 mSv/y (25 mrem/y) dose equivalent for whole-body exposures from the air pathway, and 0.75 mSv/y (75 mrem/y) dose equivalent for exposure of any organ from the air pathway.

Because the EPA standard is small and the doses caused by radionuclides released from LLNL are smaller still compared to doses from exposures to natural radioactivity, it would be difficult to prove compliance with the standard by measurements alone. EPA therefore developed computer codes that implement its approved dosimetry model and mandated that these codes be used to calculate potential doses to the public for compliance demonstrations. Calculations reported here used the EPA's CAP88-PC code. As described below in the section on Calculations of Radiological Dose, it is similar to previous regulatory codes but is improved and expanded. The models used in these codes to evaluate doses and risks contain conservative assumptions that are expected to result in calculated doses larger than ones actually received by members of the public.

Radiological Doses from Air Emissions

In accordance with DOE environmental protection orders and other federal and state requirements, LLNL assessed the radiological impact from operations at the Livermore site and Site 300 during 1994. Small amounts of radioactive materials from LLNL operations were discharged to the environment with air and water effluents (see Chapters 4, 9, and 10 regarding releases to air and Chapters 5 through 8 on water-borne releases). Because sewer effluents, as well as surface and ground waters impacted by LLNL operations, are not consumed, they do not represent an ingestion or inhalation pathway for radiation exposure. Therefore, our assessment of radiological dose to the public is based solely on material that enters the environment via air releases.

These potential radiological doses to the public are determined from both measurements of radionuclides in the environment and calculations using EPA-approved computer codes and procedures. The calculations use theoretical models for transport of radionuclides through the environment, including dispersion in air, into water and food, and finally into human beings mainly through inhalation or ingestion. Although LLNL seeks to obtain sufficient samples of the local environment to assure that its impacts are well understood, sampling for radioactivity cannot occur at all locations, and small amounts of LLNL-contributed radioactivity can be difficult to distinguish from background for some radioisotopes. The theoretical calculations are important because they set an upper bound on the potential radiological impacts of LLNL operations. The radionuclide source terms used in the codes are based on measured emissions and/or potential emissions based upon facility inventories of radioactive materials.

The results of the measurements and calculations reported in this chapter are an important indicator of the success of LLNL's radionuclide discharge control program. Development of the Livermore Valley and the San Joaquin Valley has enlarged the populations and decreased the distance between sources of emissions and the residents that might be exposed. People live and work within several hundred meters of LLNL's boundaries. It is therefore vital that our assessments provide the best information possible regarding the radiological impact of LLNL operations.

Air Emissions

Emission sources of radionuclides (stacks on buildings, drums in waste storage areas, etc.) are evaluated in two ways. For unmonitored and noncontinuously monitored sources, the releases are estimated from radionuclide inventory data using EPA methods (discussed below); for continuously monitored facilities, actual emission measurements are used. The continuously monitored facilities at LLNL are Buildings 175, 231 Vault, 251, 331, 332, 419, 490, and 491. Many of the monitored facilities show emission levels below the measurement limit-of-sensitivity (LOS), primarily due to the use of multiple-stage high-efficiency particulate air (HEPA) filters in all significant release pathways. The efficiency of a single-stage HEPA filter is 99.97%. Double-stage filter systems are in place on some discharge points. Triple-stage HEPA filters are used on glove box ventilation systems in the Building 332 Plutonium Facility and in a portion of Building 251.

Beyond the stack effluent monitoring, site-specific surveillance air monitors are placed in the vicinity of diffuse emission sources on site, such as those (described below) associated with Buildings 292, 331, 514, and 612 and in and around the southeast quadrant of the Livermore site. These special monitoring networks

measure the concentrations of radionuclides present in the air near the sources and allow a direct determination of their environmental impact.

The amount of radioactivity released from LLNL during 1994 was slightly less than in 1993 and was below the range of earlier years (see Chapter 4; especially **Tables 4-8** and **4-9**).

LLNL Areas and Buildings with Radionuclide Release Potential

All LLNL buildings that contain radioactive materials management areas (RMMAs), i.e., locations in which radionuclides are used or stored, or where activation products potentially occur, were evaluated in 1994. We also analyzed areas (generally exterior to buildings) at the two sites where diffuse emissions occur. There were 66 buildings containing RMMAs during all or part of 1994—58 on the Livermore site and eight at Site 300. **Table 12-1** lists these buildings (with some exceptions noted below), gives the number of potential radionuclide discharge points associated with each of them, lists the largest dose to a public individual due to any one of the emission points at each facility, and identifies the types of operations occurring in each facility.

Twenty-three of the RMMAs from the Livermore site and six from Site 300, in which no operations using radionuclides took place in 1994 or in which any radionuclides present were encapsulated or sealed for the entire year, are excluded from **Table 12-1**. Five Livermore site diffuse sources are listed in the table, including two of the Livermore site RMMAs (i.e., those associated with Buildings 514 and 612); six Site 300 diffuse sources are listed. Also included is information on two Site 300 explosive testing facilities associated with Buildings 801 and 851. Further details about the point and diffuse sources at both sites, and an explanation of the dose information quoted in **Table 12-1**, is provided in the Calculated Results Summary section below. A more complete description appears in the *LLNL NESHAPs 1994 Annual Report* (Surano et al. 1995).

Calculations of Radiological Dose

This section presents LLNL's methods for calculating radiological dose. It includes a description of the CAP88-PC air dispersion and dose model, principal doses and maximally exposed individuals, specification of source terms in the model runs, and a calculated results summary.

Table 12-1. Sources of radiation dose from LLNL releases to air: stacks (on buildings containing radioactive materials management areas) and diffuse area sources.[a,b]

Bldg	Facility	Potential Emission Points	Maximum EDE[c] (μSv/y)	Operations
131	Engineering	4	1.8×10^{-4}	Handling, storing, machining, characterizing, assembling, sorting, and transferring materials; repackaging of waste
151	Nuclear Chemistry	19	4.5×10^{-7}	Chemical separation, crushing/dissolving, aliquot preparation and storage, gas analysis, radiochemical separations, preparation of radioactive counting standards
175	Laser Isotope Separation	2	0.0[d]	Cleaning and refurbishing of uranium parts
177	Laser Isotope Separation	4	6.5×10^{-5}	Vaporization and coating of uranium
194	Physics & Space Technology	3	2.5×10^{-4}	Accelerator
212	Physics & Space Technology	2	8.0×10^{-11}	Environmental, safety, and health surveillance for shutdown of accelerator
222	Chemistry & Material Science	19	1.7×10^{-3}	Radioanalytical analyses and tracer use
224	Chemistry & Material Science	4	4.8×10^{-4}	Waste samples analysis
226	Chemistry & Material Science	2	5.8×10^{-9}	Radioactive and mixed waste chemical analyses
227	Chemistry & Material Science	4	2.4×10^{-6}	Uranium bonding and testing
231	Mechanical Engineering	15	1.3×10^{-2}	Materials research and testing, plastics shop work, electron beam welding
	Mechanical Engineering Vault	1	0.0[d]	Storage, handling, and shipping of radionuclides
235	Chemistry & Material Science	10	2.7×10^{-7}	Welding, actinide and uranium catalyst research
241	Chemistry & Material Science	6	3.5×10^{-9}	Materials development, measurement, and testing
251	Heavy Elements			Heavy-element research
	Hardened area	4	0.0[d]	
	Unhardened areas	7	1.4×10^{-4}	
253	Hazards Control	10	1.3×10^{-8}	Radiochemical analyses
254	Hazards Control	5	5.6×10^{-11}	Radiochemical analyses of bioassays
255	Hazards Control	1	1.0×10^{-4}	Instrument calibration
281	Chemistry & Material Science	8	5.0×10^{-9}	Preparation and storage of radiochemical stock solutions
292	Physics & Space Technology	3	7.3×10^{-5}	Tritium contamination from prior operations
298	Laser Fusion	2	1.3×10^{-6}	Handling and assembly of tritium-filled targets, sputtering uranium
321	Materials Fabrication	5	4.2×10^{-6}	Machining
331	Tritium	2	1.9×10^{-1}[d]	Decontamination and decommissioning operations
332	Plutonium	6	0.0[d]	Machining and metallurgy

Table 12-1. Sources of radiation dose from LLNL releases to air: stacks)on buildings containing radioactive materials management areas) and area diffuse area sources.[a,b] (continued)

Bldg	Facility	Potential Emission Points	Maximum EDE[c] (μSv/y)	Operations
361	Biomedical Research	24	5.8×10^{-5}	Radiolabeling; biological dosimetry; DNA sequencing, hybridization, and repair; human genome; enzyme assay; radioactive probes
362	Biomedical Research	1	2.2×10^{-7}	Dose preparation for animal experiments
363	Biomedical Research	1	1.9×10^{-5}	Dispensing samples
364	Biomedical Research	2	6.3×10^{-5}	DNA labeling; isolation and purification
365	Biomedical Research	1	6.4×10^{-12}	Housing research animals
366	Biomedical Research	2	2.5×10^{-8}	DNA sequencing; metabolization
378	Environmental Research	2	1.5×10^{-9}	Environmental analysis
381	Laser Fusion	1	2.7×10^{-13}	Tritium handling for laser target research
391	NOVA Laser	1	2.8×10^{-4}	Vaporization of targets
513	Hazardous Waste Management	3	1.3×10^{-1}	Sampling, treatment, and storage of waste; sludge stabilization
514	See diffuse sources below			
801	Site 300 Firing Table at 801	—[e]	2.0×10^{-1}	Detonation of explosives
851	Site 300 Firing Table at 851	—[e]	2.9×10^{-1}	Detonation of explosives
	Livermore site diffuse sources[f]	5	See next five entries below	Storage areas and contaminated ground
292	Physics & Space Technology	1	2.7×10^{-6}	Tank leakage area
331	Tritium	1	4.1×10^{-2}	Outdoor waste accumulation area
514	Hazardous Waste Management	1	4.6×10^{-2}	Waste treatment and storage
612	Hazardous Waste Management	1	1.3×10^{-1}	Waste storage
—	Southeast quadrant of Livermore site	1	1.1×10^{-2}	Contaminated ground

Table 12-1. Sources of radiation dose from LLNL releases to air: stacks (on buildings containing radioactive materials management areas) and diffuse area sources.[a,b] (concluded)

Bldg	Facility	Potential Emission Points	Maximum EDE[c] (μSv/y)	Operations
	Site 300 diffuse sources[f]	6	See next six entries below	Contaminated ground and water
—	Pit 7 Complex	1	6.7×10^{-4}	Contaminated ground and purge water
802	Site 300	1	1.2×10^{-6}	Contaminated ground
850	Site 300	1	1.2×10^{-4}	Contaminated ground
851	Site 300	1	3.9×10^{-7}	Contaminated ground
—	Well 8 Spring		2.4×10^{-6}	Contaminated spring water
—	Full Site 300 area	1	3.2×10^{-1}	Contaminated ground

a *LLNL NESHAPs 1994 Annual Report* (Surano et al. 1995).

b RMMAs in which no operations using radionuclides took place in 1994 or in which all radionuclides were encapsulated or sealed for the entire year are not included in this table. Table entries refer to routine operations, not unplanned releases.

c The maximum effective dose equivalent to the sitewide maximally exposed individual member of the public (SW-MEI) from a single discharge point, among all discharge points modeled for the indicated facility or building. The SW-MEI is defined in the section on Principal Doses and Maximally-Exposed Individuals.

d The effluents from the facility are and will continue to be monitored. Zeroes refer to monitored values below the limit of sensitivity, as discussed in the Air Emissions section.

e Open air dispersal in 1994.

f Diffuse sources are described briefly in the section on specifications of source terms, and more fully in the *LLNL 1994 NESHAPs Annual Report* cited in footnote a.

Description of the CAP88-PC Air Dispersion and Dose Model

EPA-mandated computer models were used to carry out our radiological dose assessments, as noted above. Early in 1992, when the CAP88-PC code became available, we began using it exclusively for our standard calculations to take advantage of the significant improvements made in the model. The CAP88-PC code was developed under an Interagency Agreement between DOE and EPA. It provides the capability to compute dose and risk to both exposed individuals and collective populations resulting from radionuclide emissions to air. The differences between CAP88-PC and earlier similar codes such as AIRDOS-PC are discussed in Appendix E of the *User's Guide for CAP88-PC, Version 1.0* (Parks 1992).

CAP88-PC uses a modified Gaussian plume equation to calculate the average dispersion of radionuclides released from up to six sources. Plume rise can be driven by momentum or buoyancy, or set to a predetermined level. Flat terrain is assumed; variation in radionuclide concentrations caused by complex terrain cannot be modeled by CAP88-PC. Assessments are done for a circular grid with a radius of 80 kilometers or less around a facility, allowing up to 20 user-selected radial distances. Concentrations and doses are sector-averaged for each area

element in the sixteen 22.5° compass sectors; each area element is bounded above and below by arcs with radii from the set of user-selected distances and on its sides by radial line segments separating the sectors. The population in each area element can be set by a user-created population data input file. The mathematical models and explicit equations used in CAP88-PC are described in Chapter 8 of Parks (1992).

CAP88-PC accepts site-specific meteorological, as well as population, data files. Input data for the LLNL modeling are collected from on-site meteorological towers at both the Livermore site and Site 300. Wind speed and direction are sampled every few seconds, temperature every minute, and all are averaged into quarter-hour increments, time-tagged, and computer-recorded for conversion into a CAP88-PC wind file. Numbers specifying the annual average precipitation, temperature, and average height of the atmospheric inversion layer are also put into the model. The code automatically computes results for each of seven Pasquill-Gifford atmospheric stability categories.

CAP88-PC computes radionuclide concentrations in air, rates of deposition on ground surfaces, concentrations in food, and intake rates to people from ingestion of food produced in the assessment area. Calculated doses then include the four principal exposure pathways: internal exposures from inhalation of air and ingestion of foodstuffs and drinking water, and external exposures through irradiation from contaminated ground and immersion in contaminated air. Dose and risk are tabulated as a function of radionuclide, pathway, spatial location, and body organ. Up to 36 radionuclides can be included in a single run, chosen from a total library of 265 radionuclides. The frequency distribution of risk is tabulated, showing the number of people at various levels of risk on a logarithmic scale from one in ten to one in ten million. Dose and risk estimates from CAP88-PC are applicable only to low-level chronic exposures because the health effects and dosimetric data it uses are based on low-level chronic intakes. The code is not intended for modeling either short-term or high-level radionuclide intakes. The doses are expressed as whole-body effective dose equivalents (EDEs) in units of mrem / y (1 mrem = 10 μSv = 0.01 mSv).

Because CAP88-PC does not contain all the radionuclides present at LLNL, surrogate radionuclides were used in some cases to estimate EDEs. In selecting the surrogates, we used the most restrictive lung class (whether clearance from the lungs takes place in days, weeks, or years). When possible, we used a surrogate radionuclide with similar lung class chemistry and similar values for "annual limits of intake via inhalation and derived air concentration," as specified in the EPA guidance, *Limiting Values of Radionuclide Intake and Air Concentration and Dose Conversion Factors for Inhalation, Submersion, and Ingestion* (Eckerman et al. 1988). CAP88-PC contains a library of considerably more radionuclides than earlier regulatory codes, such as AIRDOS-PC. By rerunning

calculations with CAP88-PC previously modeled with AIRDOS-PC, we have found that the use of surrogates in the calculations typically results in conservative estimates of EDEs.

Principal Doses and Maximally-Exposed Individuals

We report separate determinations of doses for the Livermore site and Site 300. Three potential doses are emphasized: (1) The dose to the sitewide maximally exposed individual member of the public (denoted as SW-MEI and defined below), which combines the effects of all emission points; (2) the maximum dose to any member of the public, in any direction (generally occurring at the site boundary and commonly referred to as the maximum "fenceline" dose) due to each emission point on the site; and (3) the collective dose to the populations residing within 80 kilometers of the Livermore site and Site 300 (treated separately), adding the products of individual doses received and the number of people receiving them. Dose (1) is used to evaluate LLNL's compliance with the EPA standard limiting the total radionuclide emissions to air from DOE facilities to 100-μSv/y (10-mrem/y) (NESHAPs, 40 CFR Part 61.92, Subpart H). In this evaluation, credit is taken for any emission abatement devices, such as filters, that are in place. Dose (2), which is calculated without regard for any existing emission abatement devices, is used to evaluate the need for continuous monitoring of individual emission points under the EPA's 1-μSv/y (0.1-mrem/y) standard on potential unabated emissions (40 CFR Part 61.93).

The SW-MEI is defined as the hypothetical member of the public (individual receptor at a residence, place of business, school, church, or similar public facility) who could receive the greatest LLNL-induced EDE from all sources at a single site. At the Livermore site, the SW-MEI is located at the UNCLE Credit Union, about 10 meters outside the controlled eastern perimeter of the site. This location lies 948 meters from LLNL's principal radionuclide source, the Tritium Facility (Building 331), in an east-northeast direction. At Site 300, the SW-MEI is located in an experimental area termed "Bunker 2" operated by Physics International. Bunker 2 lies about 300 meters outside the east-central boundary of Site 300. This bunker is 2.4 kilometers east-southeast of the principal firing table at Building 801.

It is possible for the location of the SW-MEI to change from year to year, e.g., with changing wind patterns, changing population distributions near site boundaries, or changing emission levels of sources. An illustration of the effect of different wind patterns on dose is given in the *LLNL NESHAPs 1993 Annual Report* (Harrach et al. 1994). Four prime candidates for the SW-MEI were evaluated for the Livermore site in confirming the UNCLE Credit Union location for 1994, as described in the *LLNL NESHAPs 1994 Annual Report* (Surano et al. 1995).

Specification of Source Terms in the Model Runs; Point and Diffuse Sources

The source term for each emission point in the calculations was arrived at by one of two methods, as noted earlier. For continuously monitored sources, the data on curies released per unit time for each radionuclide were used directly as input variables into the modeling codes. For unmonitored or noncontinuously monitored facilities, we relied on inventories, together with EPA-specified fractions for potential release to air of materials in different physical states (solid, liquid, powder, or gas), in accordance with 40 CFR Part 61, Subpart H, Appendix D. Use of the state-dependent potential release fraction adjusts (by multiplication) the total annual inventory to give the potential annual release to air. If the material was an unconfined gas, then the release fraction 1.0 was used; for liquids and powders, 1.0×10^{-3} was used; and for solids, 1.0×10^{-6} was used. In addition, credit was taken for radionuclide emission control devices when calculating total dose for evaluation under the 10 mrem/y (100 μSv/y) EPA standard; e.g., each stage of HEPA filtration produces a 1.0×10^{-2} emission-reduction factor. However, emissions were assumed to be unabated for evaluations under the 1 μSv/y (0.1 mrem/y) EPA standard for required continuous monitoring.

Monitored Facilities

Dose calculations based on actual monitoring data are expected to be more accurate than those using assumptions based on inventory data, physical state release fractions, and emission-control factors. Among the eight continuously monitored facilities at the Livermore site, discussed earlier—Buildings 175, 231 Vault, 251, 331, 332, 419, 490, and 491—none require monitoring under the EPA 1 μSv/y (0.1 mrem/y) standard. Nonetheless, continuous monitoring is maintained at all of these facilities for programmatic reasons. For example, continuous monitoring is maintained at Building 331 (the Tritium Facility) to provide the most direct and accurate measure of its release of tritium to the atmosphere, even though the EDEs we calculate from measured unabated emissions are below the 1 μSv/y (0.1 mrem/y) level (see **Table 12-1**). No additional facilities at either the Livermore site or Site 300 were found to require continuous monitoring systems under the EPA standard.

Inventoried Facilities

For this year's NESHAPs annual report, covering activities in 1994, the radionuclide inventories for all unmonitored or noncontinuously monitored Livermore-site facilities containing RMMAs were updated. Inventory forms, accompanied by detailed guidance for completing them, were sent to all of these facilities, filled out by experimenters, certified by facility managers, and returned. We also compiled new inventories for all Site 300 explosive experiments and performed new assessments of all diffuse sources we have identified at the two sites. New

dose-assessment modeling runs, using 1994 on-site meteorological data (wind, precipitation, and temperature) along with the 1994 radionuclide inventory or monitoring data, were conducted for every emission point.

Explosive Tests at Site 300

Modeling the releases to the atmosphere from explosive tests using depleted uranium at Site 300 requires special attention compared to conventional stack or area sources. During experiments, the explosive device containing depleted uranium is placed on an open-air firing table and detonated. We have limited data to characterize the initial state of the cloud of explosive decomposition products created by the detonation because properties of the cloud are not typically measured in the experiments. However, well-known empirical scaling laws for cloud height and size can be used that only require knowledge of the quantity of high explosive driving the detonation. Isotopic ratios for depleted uranium are used. The masses of the three uranium isotopes with atomic weights 238, 235, and 234 (occurring in depleted uranium in the weight-percentages 99.8, 0.2, and 5×10^{-4}, respectively) are multiplied by their respective specific activities to get the total number of curies for each isotope in the cloud. We assume all of the depleted uranium is dispersed into the cloud, and the median particle size is assumed to be the CAP88-PC default value of 1 micrometer. This assumption that all uranium is aerosolized and dispersed as a vapor produces a highly conservative off-site dose. We believe a more realistic release-to-air fraction for the uranium is no greater than 0.2, but we lack sufficient justification to use a value other than 1.0. CAP88-PC simulates each shot as a low-level, steady-state, stack-type emission occurring over one year. An alternative modeling methodology for treating these short-duration explosive events was submitted for approval in 1992 (*LLNL NESHAPs Project Quarterly Progress Repor*t, Biermann et al. 1993), but LLNL was directed by EPA to use the CAP88-PC code for these calculations despite the recognized difficulties.

Diffuse Sources

Another category of sources requiring special attention is diffuse emissions, including fugitive emissions. Diffuse, or nonpoint, sources often are difficult to quantify. Presently, methods of dose calculations associated with them are left to the discretion of the DOE facility although proposed guidance was sent out by EPA in 1993 for review.

Four different modeling approaches were used for diffuse sources at LLNL's Livermore site in 1994. Elevated tritium levels in soil moisture near Building 292 required a calculation of the source term and the use of CAP88-PC. Estimated releases from tritium-contaminated equipment outside Building 331 were

derived from measurements of surface contamination, process and facility knowledge, and environmental surveillance measurements. Radioactive wastes stored in the Building 612 Yard required environmental surveillance data to estimate emissions. For Building 514, which houses the Hazardous Waste Management tank farm for waste processing and storage, radiological-inventory data were used with standard CAP88-PC modeling techniques. Direct ambient air monitoring of plutonium in surface soils in the southeast quadrant of the Livermore site provided data on which to base dose calculations.

Diffuse sources at Site 300 involve tritium and uranium. Their evaluation was based on data provided in the *Final Site-Wide Remedial Investigation Report Lawrence Livermore National Laboratory Site 300* (Webster-Scholten 1994), where potential routes of tritium and uranium migration from soil to air were identified and evaluated. These radionuclides were components of the explosives assemblies tested on the Site 300 firing tables over many years. Five diffuse sources of tritium (the Pit 7 Complex, Well 8 Spring, and ground areas associated with Buildings 802, 850, and 851) were characterized, and diffuse sources of uranium were treated collectively in a resuspension calculation tied to air-particulate sampling data. A description of each source at the two sites and the assumptions made regarding their emissions is given in the *LLNL NESHAPs 1994 Annual Report* (Surano et al. 1995).

Calculated Results Summary—Livermore Site and Site 300, 1994

Table 12-1, as discussed earlier, summarizes the sources of the radiation dose from airborne radionuclides emitted by routine LLNL operations in 1994. In particular, the number of potential discharge points at each facility is given, along with the largest EDE value from any one discharge point at each facility. Corresponding information is given for Site 300 facilities and for the diffuse sources at both sites.

There was one unplanned atmospheric radionuclide release at the Livermore site in 1994 and none from Site 300. In December 1994, during transfer of boxes containing depleted-uranium ingots, several ingots fell out of the boxes onto the sidewalk, curb, and grass area southwest of Building 241, along Avenue B at the Livermore site. The spilled ingots and associated contamination were promptly cleaned up; less than 370 Bq (0.01 μCi) remained as residual contamination in the spill area. Modeling evaluated the resultant maximum dose to a member of the public from the residual contamination to be less than 6.8×10^{-12} μSv / y (6.8×10^{-13} mrem / y), far below levels of health concern.

Table 12-2 lists the facilities that were primarily responsible for the LLNL dose; the contributions from all emission points at each facility have been summed. These facilities accounted for 98% of the total EDE resulting from Livermore-site operations and nearly 100% of the total EDE from Site 300 operations. The

Table 12-2. Major contributors to LLNL's radiation dose via airborne emissions, 1994.

Facility or Operation[a]	Dominant Radionuclide(s)	EDE at SW-MEI[b]	
		μSv/y	mrem/y
Livermore site			
B331/Tritium Facility	^{3}H	0.27	0.027
B612 Yard Area[c]	^{3}H	0.13	0.013
B513	^{241}Am, ^{238}U, ^{234}U, ^{228}Th	0.13	0.013
B514[c]	^{238}U, ^{235}U, ^{234}U, ^{241}Am	0.046	0.0046
B331 Exterior[c]	^{3}H	0.041	0.0041
B231	^{238}U, ^{234}U, ^{235}U	0.014	0.0014
SE Quadrant[c]	^{239}Pu	0.011	0.0011
Sum of other sources	Various	0.010	0.0010
	Total =	0.65[d]	0.065[d]
Site 300			
B851/firing table	^{238}U, ^{234}U, ^{235}U	0.29	0.029
B801/firing table	^{238}U, ^{234}U, ^{235}U	0.20	0.020
Soil resuspension[c]	^{238}U, ^{234}U, ^{235}U	0.32	0.032
Total		0.81[d]	0.081[d]

a The facilities cited here are discussed in the text of this report, and in more detail in the NESHAPs annual reports.

b These doses represent the sum of all emission points from a given facility (for example, both stacks on Building 331), in contrast to the dose values in Table 12-1, which represent the dose from the single largest emission point on each facility. The site-wide maximally exposed individual member of the public (SW-MEI) is defined in the section on Principal Doses and Maximally-Exposed Individuals.

c Diffuse sources (see text).

d These Livermore site and Site 300 totals represent 0.7% and 0.8%, respectively, of the federal standard.

dominant radionuclide(s) are indicated for each facility. Tritium accounted for about 68% of the Livermore-site dose, and uranium (principally uranium-238) for 16%. At Site 300, practically the entire dose was due to the isotopes uranium-238, -235, and -234 comprising depleted uranium.

The relative significance of inhalation and ingestion is different for tritium and uranium, and depends on the assumptions made about the origin of food consumed by a person receiving the dose. As in previous years, we employed the local agriculture option in CAP88-PC, where all food consumed is assumed to be locally grown at receptor locations and therefore maximally affected by the emissions from sources upwind. This option produces the maximum dose to the SW-MEI, and therefore is the most conservative of the six agricultural-land-use options available in CAP88-PC: urban, rural, local, regional, imported, and user-specified. We then find that, for the meteorological conditions and source emission characteristics at LLNL in 1994, ingestion was most important in the

case of tritium, contributing 86% of the dose, versus 14% for inhalation. For uranium, these numbers were nearly reversed: inhalation accounted for 89% of the dose, versus 11% for ingestion. For both uranium and tritium, external doses from air immersion and ground irradiation were negligible.

Maximum Dose to an Individual Member of the Public

The calculated EDE to the SW-MEI from point source emissions at the Livermore site in 1994 was 0.42 μSv (0.042 mrem), and from diffuse source emissions was 0.23 μSv (0.023 mrem). Summing these contributions yields a total dose of 0.65 μSv (0.065 mrem) for the Livermore site in 1994—65% from point sources, 35% from diffuse. The leading contributors were 0.27 μSv (0.027 mrem) due to emissions from the two 30-meter stacks at the LLNL Tritium Facility (Building 331), 0.13 μSv (0.013 mrem) from the Building 612 Yard diffuse source, and 0.13 μSv (0.013 mrem) from the Building 513 waste-processing stabilization unit.

Compared to data of previous years, the total of 0.65 μSv (0.065 mrem) for 1994 is practically the same as the 1993 value of 0.66 μSv (0.066 mrem), slightly below the 1992 value of 0.79 μSv (0.079 mrem), and well below the dose values of 2.34 μSv (0.234 mrem) and 2.40 μSv (0.240 mrem) reported for 1991 and 1990, respectively.

The total dose to the SW-MEI at Site 300 during 1994 was calculated to be 0.81 μSv (0.081 mrem). Explosive tests at the Building 801 and Building 851 firing tables accounted for all of the point source dose of 0.49 μSv (0.049 mrem), while a source representing resuspension of both naturally-occurring and LLNL-contributed uranium in surface soils throughout the site was responsible for nearly all of the diffuse sources total of 0.32 μSv (0.032 mrem).

Table 12-3 shows the firing table dose values for 1990 through 1994, correlated with the total amounts of depleted uranium and the total quantity (TNT-equivalent) of high explosives used in the experiments. (Only experiments that included depleted uranium are considered; most have none.) The data show that variations from year-to-year in these doses mainly reflect differences in the amount of depleted uranium used in the tests.

The amount of depleted uranium also affects, to a smaller degree, the diffuse-source dose, by contributing to the general contamination of soil at the site. Comparing Site 300 diffuse source contributions in 1994 and 1993, we find a 23% increase in dose from resuspended uranium in 1994, when 2.3-times more depleted uranium was used. Comparison of the diffuse source contributions for earlier years cannot be made because we did not evaluate Site 300's diffuse emissions prior to 1993.

Table 12-3. Annual dose to the SW-MEI from explosives experiments on firing tables at Site 300, 1990–1994, related to the total quantity of depleted uranium used in the experiments and the total quantity of high-explosives (HE) driving the detonations.

Year	Dose to SW-MEI (μSv)	Dose to SW-MEI (mrem)	Total depleted U used in experiments (kg)	Total HE used in depleted U experiments (kg)
1994	0.49	0.049	230	134
1993	0.11	0.011	99	74
1992	0.21	0.021	151	360
1991	0.44	0.044	221	330
1990	0.57	0.057	340	170

The trends in dose to the SW-MEI from emissions at the Livermore site and Site 300 over the last five years are shown in **Figure 12-2**. The Site 300 dose values for 1990, 1991, and 1992 include no contributions from diffuse sources, as noted above. The levels of public exposure indicated in **Figure 12-2** are well below the EPA standard, which limits the whole-body air-pathway EDE to members of the public from DOE activities to 100 μSv/y (10 mrem/y).

Table 12-4 compares the radiation doses from atmospheric emissions at LLNL to other sources of radioactivity to which the U.S. population is exposed. The dose to the maximally exposed member of the public resulting from Livermore-site and Site 300 operations is seen to be about one four-thousandth of the doses from background radiation (see also **Figure 12-1**). **Table 12-4** shows that radon emissions rank highest among the sources of natural radioactivity, contributing an average dose of 2.0 mSv/y (200 mrem/y). Radon emissions from LLNL operations are very small. Radon-222 emissions from research experiments during 1994 were estimated to be 7.4×10^5 Bq (20 μCi), with a corresponding EDE of 3×10^{-8} μSv (3×10^{-9} mrem). These ^{222}Rn emissions are less than one-millionth of that expected for naturally occurring ^{222}Rn emanation from the soil of the LLNL's Livermore site.

Collective Doses to Exposed Populations

Population doses, or collective EDEs, for both LLNL sites were calculated out to a distance of 80 kilometers in all directions from the site centers using CAP88-PC. As noted earlier, CAP88-PC evaluates the four principal exposure pathways for releases to air: ingestion through food and water consumption, inhalation, air immersion, and irradiation by contaminated ground surface.

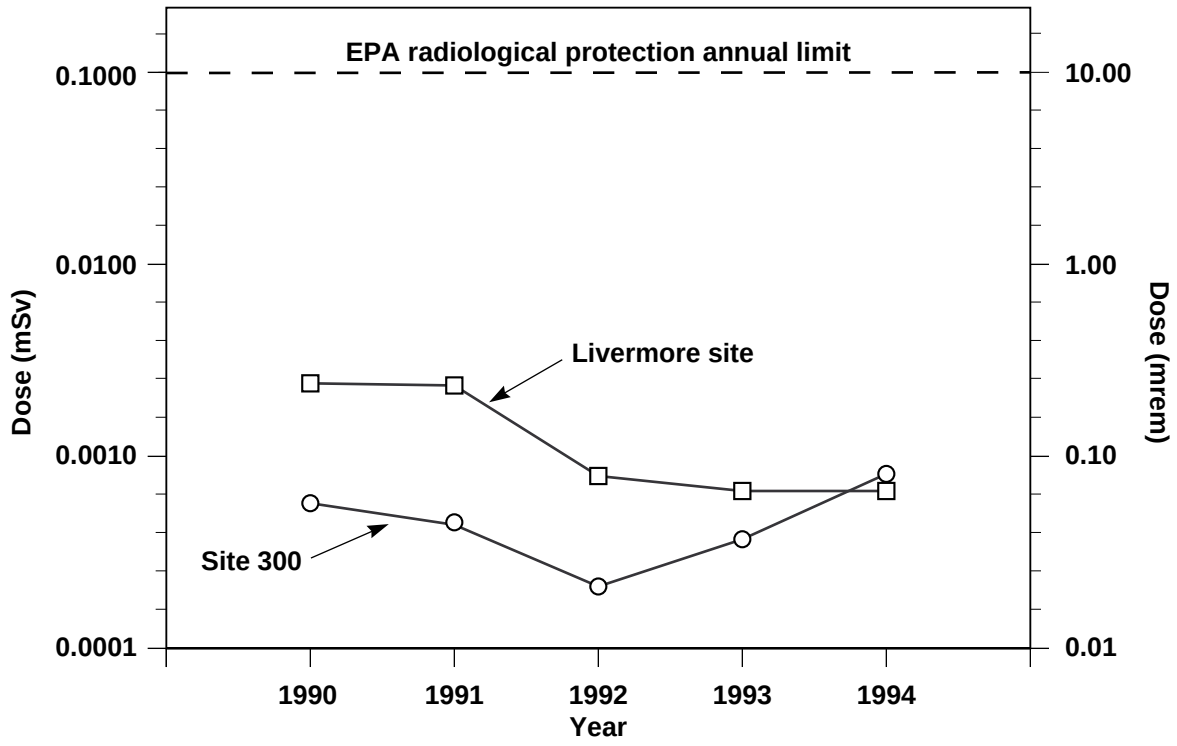

Figure 12-2. Maximum calculated air pathway dose at LLNL, sitewide maximally exposed public individual, 1990 to 1994.

Population distributions centered on the two LLNL sites were compiled from 1990 census data. Key population centers affected by LLNL emissions are the relatively nearby communities of Livermore and Tracy, and the more distant metropolitan areas of Oakland, San Francisco, and San Jose, as well as the San Joaquin Valley communities of Modesto and Stockton. Within the 80-kilometer outer distance specified by the EPA, there are 6.3-million residents included for the Livermore site collective dose determination, and 5.4 million for Site 300. (Since the two sites are separated by 24 kilometers, some of the residents are common to both determinations.) Our population data files, specifying the distribution of population with distance and direction, are described in the *LLNL NESHAPs 1994 Annual Report* (Surano et al. 1995).

The collective EDE due to 1994 Livermore-site operations was 0.0076 person-Sv (0.76 person-rem), of which 0.0050 person-Sv (0.50 person-rem), or 66%, was from point-source emissions, and the remaining 34% from diffuse sources. This value is down slightly from the 1993 result of 0.0098 person-Sv (0.98 person-rem), and is less than half of the 0.017 person-Sv (1.7 person-rem) collective EDE caused by Livermore-site operations in 1992.

Table 12-4. Comparison of background and LLNL radiation doses, 1994.

Location/Source	Individual Dose[a]		Population Dose[b]	
	(mSv)	(mrem)	(person-Sv)	(person-rem)
Livermore-site sources				
Atmospheric emissions	0.00065	0.065	0.0076	0.76
Site 300 sources				
Atmospheric emissions	0.00081	0.081	0.17	17
Other sources[c]				
Natural radioactivity[d,e]				
Cosmic radiation	0.3	30	1,900	190,000
Terrestrial radiation	0.3	30	1,900	190,000
Internal (food consumption)	0.4	40	2,500	250,000
Radon	2.0	200	12,500	1,250,000
Medical radiation (diagnostic procedures)[e]	0.53	53	3,300	330,000
Weapons test fallout[e]	0.011	1.1	68	6,800
Nuclear fuel cycle	0.004	0.4	25	2,500

a For LLNL sources, this dose represents that experienced by the sitewide maximally exposed individual member of the public.

b The population dose is the collective (combined) dose for all individuals residing with an 80-kilometer radius of LLNL (approximately 6.3 million people for the Livermore site and 5.4 million for Site 300), calculated with respect to distance and direction from each site.

c From National Council on Radiation Protection (NCRP 1987).

d These values vary with location.

e This dose is an average over the U.S. population.

The corresponding collective EDE from Site 300 operations in 1994 was 0.17 person-Sv (17 person-rem), comprised of 0.14 person-Sv (14 person-rem), or 82%, due to point-source emissions, and 0.028 person-Sv (2.8 person-rem) from diffuse-source emissions. This total is more than two times the values of 0.069 person-Sv (6.9 person-rem) and 0.071 person-Sv (7.1 person-rem) calculated for 1993 and 1992, respectively, caused primarily by the increased amount of depleted uranium used in explosives experiments in 1994 (**Table 12-3**).

The larger collective dose for Site 300 than for the Livermore site is traceable primarily to our highly conservative, health protective assumptions about the Site 300 explosives experiments, especially regarding the fraction of radioactive material that is aerosolized and the height and trajectory of the explosive-debris cloud. As noted earlier, this conservative modeling methodology over-predicts

the quantity of radionuclides released to air by at least a factor of five, we believe, and over-estimates the long-range dispersal of material in these experiments.

We note that the diffuse sources influence the individual dose to the SW-MEI more than they impact the population dose. The reason is the relatively less dynamic nature of the diffuse-source emissions, originating low to the ground at low initial velocity. Stacks release effluents at considerable speed high above the ground, and the explosives experiments force the effluent high into the air, allowing contaminants to be more readily transported toward population centers downwind.

Summary and Conclusion

The annual radiological dose from all emissions at the Livermore site and Site 300 in 1994 was found to be well below the applicable standards for radiation protection of the public, in particular the NESHAPs standard for DOE facilities, which limits total annual emissions of radionuclides to the ambient air to 100 μSv / y (10 mrem / y).

Using EPA-mandated computer models, actual LLNL meteorology, and population distributions appropriate to the two sites, the dose to the maximally exposed public individual was found to be 0.65 μSv (0.065 mrem) from Livermore site emissions and 0.81 μSv (0.081 mrem) from Site 300. These amount to about 0.7% and 0.8% of the standard, respectively, and are about 4,000-times smaller than the dose received by these populations from natural background radiation. The major radionuclides accounting for the doses were tritium at the Livermore site, and the three isotopes in depleted uranium (^{238}U, ^{235}U, and ^{234}U) at Site 300.

The collective effective dose equivalent or population dose for LLNL 1994 operations was calculated to be 0.0076 person-Sv (0.76 person-rem) from Livermore-site operations and 0.17 person-Sv (17 person-rem) from Site 300. These doses include exposed populations of 6.3 million people for the Livermore site and 5.4 million for Site 300, living within a distance of 80 kilometers from the site centers, based on 1990 census data. These numbers are small fractions of the population dose due to natural radioactivity in the environment: 18,800 person-Sv (1,880,000 person-rem).

We conclude that the potential radiological doses from LLNL operations were well within regulatory standards and very small compared to doses normally received by these populations from natural background radiation sources, even though highly conservative assumptions were used in the calculations. Thus, the maximum credible doses show that LLNL's use of radionuclides had no significant impact on public health during 1994.